PHYSICAL REVIEW B VOLUME 58, NUMBER 5 1 AUGUST 1998-I

Resistivity investigations of plastic vortex creep in $YBa_2Cu_3O_{6.95}$ crystals

A. V. Bondarenko, V. A. Shklovskij, M. A. Obolenskii, R. V. Vovk, and A. A. Prodan
Kharkov State University, Svoboda sq. 4, 310077, Kharkov, Ukraine

M. Pissas,* D. Niarchos, and G. Kallias
Institute of Materials Science, NCSR ''Demokritos,'' 15310 Ag. Paraskevi, Athens, Greece

(Received 29 December 1997)

The current-voltage characteristics (CVC's) of $YBa_2Cu_3O_{6.95}$ single crystal with unidirectional twins were measured in external magnetic field inclined with respect to twin planes under the angle 45°. Current, magnetic-field, and temperature dependences of the pinning potential $U(J,B,T)$ and magnetic-field and temperature dependences of the depinning critical current $J_c(B,T)$ were derived from the CVC's. It is shown that in high magnetic fields $U(J,B,T)$ comes in terms with dislocation-mediated plastic creep vortex lattice. [S0163-1829(98)01430-1]

I. INTRODUCTION

Recent investigations of local magnetic relaxation at $T=85$ K in $YBa_2Cu_3O_{6.95}$ single crystals[1] showed that vortex dynamics at low and high magnetic fields are quite different. At low magnetic fields the activation energy U of vortex creep increases with the field as $U\sim B^{1.2}$. This behavior qualitatively agrees with collective pinning theory[2] based on the concept of elastic motion of the vortex lattice. At high magnetic fields the activation energy decreases with increasing field in contrast to the predictions of collective pinning theory. In Ref. 1 this behavior was attributed to dislocation-mediated plastic creep. When the vortices are at an angle θ with respect to the a-b plane, the activation energy, at $J=0$, of such creep is given by

$$U_{pl}^0(B,T)\approx\varepsilon_\vartheta\varepsilon_0 a\varepsilon_\theta^{1/2}\sim(T_c-T)B^{-\nu}, \qquad (1)$$

where $\varepsilon_0=(\Phi_0/4\pi\lambda)^2$ is the vortex line tension,[2] $a\approx(\Phi_0/B)^{1/2}$ is the mean isotropic intervortex distance, Φ_0 is the flux quantum, λ is the magnetic penetration depth, $\varepsilon_\vartheta=(\varepsilon^2\cos^2\vartheta+\sin^2\vartheta)^{1/2}$ [$\vartheta+\theta=\pi/2$, $\varepsilon=(m/M)^{1/2}$ is the mass anisotropy], and $\nu=1/2$. Here we assumed that flux diffusion of dislocation occurs along the minimal intervortex distance $a_\vartheta\approx\varepsilon_\vartheta^{1/2}a$ in the anisotropic flux-line lattice. Assuming that the current dependence of the activation energy is taken from the dislocation theory[3]

$$U_{pl}(J)=U_{pl}^0[1-(J/J_c^{pl})^\mu], \qquad (2)$$

where $\mu=1/2$ and J_c^{pl} is the critical current that corresponds to the plastic motion, the authors of Ref. 1 derived a dependence $U_{pl}^0(B)\sim B^{-\nu}$ ($\nu=-0.7$) from their data. The difference between the predicted, $\nu=-1/2$, and the experimental, $\nu_{\text{exp}}=-0.7$, values of exponent ν was explained by the vicinity to the melting transition.

II. RESULTS AND DISCUSSION

The aim of this paper is the investigation of vortex dynamics in $YBa_2Cu_3O_{6.95}$ single crystals in the range of magnetic fields where dislocation-mediated vortex creep is expected. We present current-voltage characteristics of a bridge cut out from a single crystal with dimensions $3\times3\times0.02$ mm^3. The smallest dimension corresponds to the c axis of the crystal. The dimensions of the measured part of the bridge were 0.2×0.2 mm^2. The critical temperature of the sample was $T_c\approx92$ K and the width of the transition in zero magnetic field was $\Delta T_c\approx0.3$ K. Twin boundaries inside the bridge were oriented in one direction. Transport current was applied parallel to the ab plane at an angle of 7° with respect to the twin planes. The magnetic-field vector was perpendicular to the transport current vector and was oriented to 45° with respect to both the c axis and the twin planes. At such a high misorientation angle between H and the twin planes, the vortex lines are not deformed by the twin planes and pinning at the twin boundaries is equivalent to pinning by point defects.

Current voltage characteristics (CVC's) were measured with dc-current technique for opposite directions of the current vector. To improve thermal contact the sample was attached to a massive copper block with glue BF-2. The block's temperature stability was about 3 mK. Measurements at temperatures above T_c show that overheating of the sample at the highest dissipation level 7×10^{-5} W did not exceed 10 mK.

Figure 1(a) shows CVC's measured at $T=85.1$ K. For magnetic fields $5<H<13$ kOe the $E(J)$ dependence is linear in a ln$E$ vs $J^{1/2}$ plot, and thus the current dependence of the electric field obeys the equation

$$E(J)=E_0\exp\{-U^0(B,T)[1-(J/J_c)^\mu]/kT\}, \qquad (3)$$

where E_0 is a constant, k is Boltzmann's constant, and $\mu=1/2$. For higher magnetic fields, $H>13$ kOe, we observed negative curvature in the $E(J)$ dependence, which confirms that exponent μ is smaller than 1/2. The field dependence of μ is presented in Fig. 2 by open circles. Figure 1(b) shows CVC's measured at a magnetic field $H=14.4$ kOe. For $T<84$ K, the $E(J)$ dependence obeys Eq. (3) with $\mu=1/2$, and for higher temperatures exponent μ decreases, leading to negative curvatures of the $E(J)$ dependence, when plotted in a ln$E$ vs $J^{1/2}$ plot. The temperature dependence of μ is

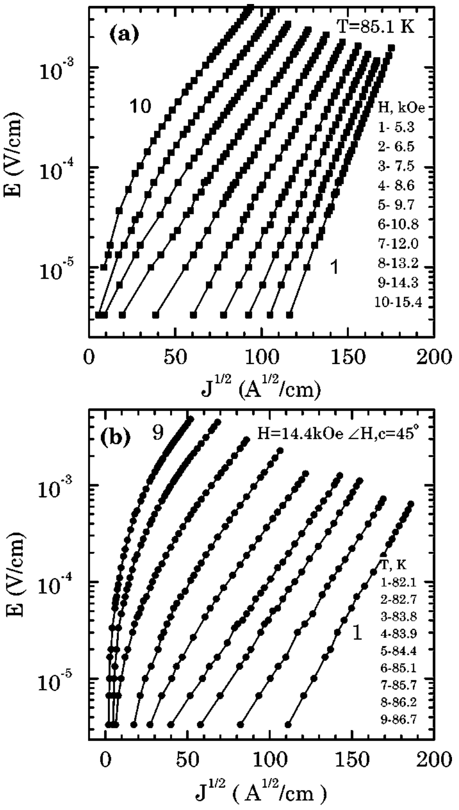

FIG. 1. (a) Currrent-voltage characteristics measured at $T=85$ K in various magnetic fields (5.3–10.5 kOe). (b) Currrent-voltage characteristics measured at $H=14.4$ kOe for various temperatures (82.1–86.7 K). The lines are guides to eye.

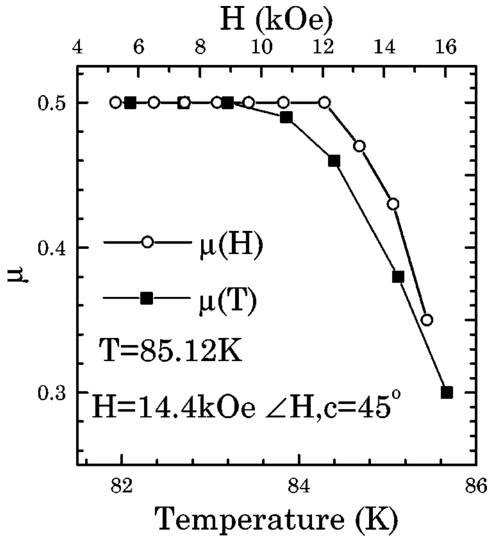

FIG. 2. Temperature and field dependence of the exponent μ that appears in Eq. (2).

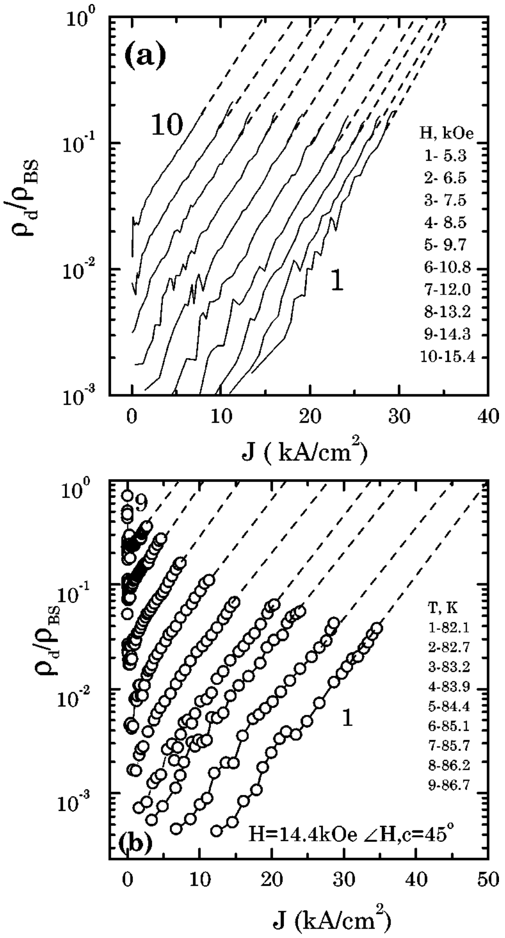

FIG. 3. (a) Normalized differential resistivity ρ_d/ρ_{BS} ($\rho_d=dE/dJ$, $\rho_{BS}=\rho_N B/H_{c2}$) at $T=85.1$ K as a function of the dc-current density for several external dc magnetic fields ($H=5.3$, 6.5, 7.5, 8.6, 9.7, 10.8, 12, 13.2, 14.3, and 15.4 kOe). J_c as a function of the dc magnetic field was determined from linear extrapolation of ρ_d/ρ_{BS} to unity. (b) Normalized differential resistivity ρ_d/ρ_{BS} as a function of the current density at $H=14.5$ kOe for several temperatures ($T=82.1$, 82.7, 83.2, 83.9 84.4, 85.1, 85.7, 86.2, and 86.7 K).

shown by solid squares in Fig. 2. As it can be seen in Fig. 2, far below the vortex lattice melting the value of μ agrees with the one predicted for dislocation-mediated plastic creep of vortex lattice. The values of $U^0(B,T)$ can be extracted from the measured CVC's if the critical current density J_c is known. J_c can be estimated from the Bardeen-Stephen behavior of flux flow resistivity. Experimental investigations of $NbSe_2$ and $YBa_2Cu_3O_{6.95}$ single crystals showed that the differential resistivity $\rho_d=dE/dJ$ does not depend on the current for transport current densities higher than J_c and agrees with the values obtained in the Bardeen-Stephen approach,[4]

$$\rho_{BS}=\rho_N B/H_{c2}, \tag{4}$$

where ρ_N is the resistivity in the normal state, B is the magnetic induction, and H_{c2} is the upper critical field. Therefore, the value of the critical current can be estimated by assuming $J=J_c$ when $\rho_d=\rho_{BS}$. The current dependence of normalized $\rho_d(\rho_d/\rho_{BS})$ is shown in Fig. 3. The curves in this figure correspond to curves presented in Fig. 1. The value of ρ_N was determined by extrapolating the linear part of the $\rho(T)$ variation. The values of H_{c2} were estimated by assuming $dH_{c2}/dT=-18$ kOe/K for $H\|c$, $H_{c2}(T,\theta)=(dH_{c2}/dT)(T-T_c)/\varepsilon_\vartheta$, and $\varepsilon=1/6$. As demonstrated in Fig. 3 $\rho_d<\rho_{BS}$ for all the investigated current windows. It is also seen that for high values of J the $\rho_d(J)$ dependence is linear in semilogarithmic scale. Therefore we estimated the values of J_c by extrapolating the ρ_d/ρ_{BS} curves to unity, as shown in Fig. 3. Substituting the estimated values of J_c in

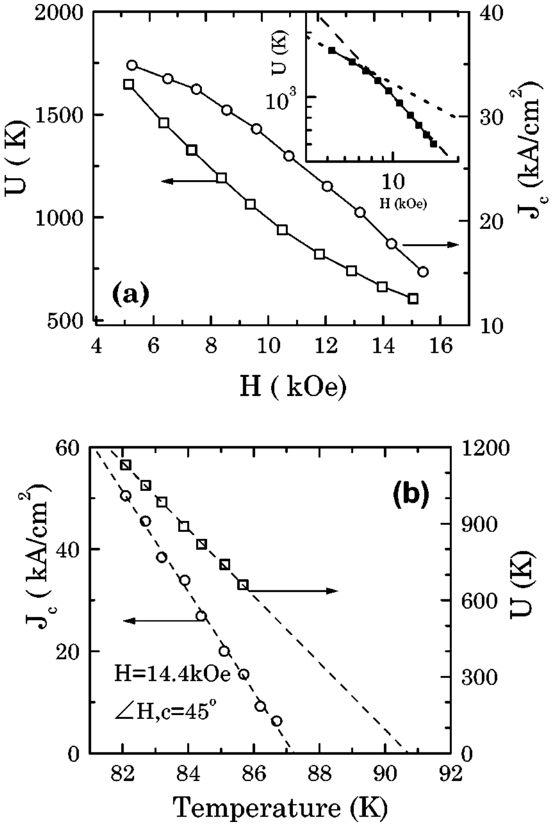

FIG. 4. (a) Field dependence of the critical current density $J_c(H)$ and pinning potential $U^0(H)$ at $T=85$ K. (b) Temperature dependence of the critical current density $J_c(T)$ and pinning potential $U^0(T)$ for $H=14.4$ kOe. Inset shows the variation of $U^0(H)$ with H at $T=85$ K in a double-logarithimic plot.

Eq. (3) and extrapolating the experimental data by it, we obtained the values of the activation energy U^0. The derived field and temperature dependences of J_c are shown by open circles in Figs. 4(a) and 4(b), respectively. Open squares in Figs. 4(a) and 4(b) show, respectively, field and temperature dependencies of U^0 obtained by fitting the $E(J)$ data, using Eq. (3). The value of U^0 decreases with increasing field or with increasing temperature. The inset to Fig. 4(a) shows the dependence $U^0(H)$ in a double logarithmic scale. It is seen that it is not possible to fit $U^0(H)$ data by the dependence $U^0(H) \sim H^{-\nu}$ with a constant value of ν. Nevertheless, the slope -0.55 of the $U(H)$ dependence at lowest fields is in good agreement with the $\nu=1/2$ value predicted for dislocation-mediated creep of the vortex lattice. It should also be noted that the change of the slope of $E(J)$ curves presented in Fig. 1(a) obeys an $\sim H^{-0.77}$ law. The value $\nu=0.77$ is close to the $\nu=0.7$ value obtained in Ref. 1 for the field dependence of the activation energy.

The $E(J)$ curves presented in this paper when replotted in ln$E$-ln$J$ scale have positive curvature in contrast to the negative one previously observed in thin films[5] and twinned single $YBa_2Cu_3O_{6.95}$ crystals.[6] The question arises as to whether this discrepancy is the ''effect of sample'' or not. The critical current in films is at least one order of magnitude higher than in single crystals and negative curvature may indicate another mechanism of vortex creep in such strongly disordered samples as films. The results of our measurements, which are not presented here, show that the positive curvature is replaced by negative for misorientation angles between **H** and twin planes smaller than 20°, or in the range of angles where the effect of twin planes on pinning and dynamics of vortices is significant. Thus our results correlate with those reported in the literature if **H** is applied parallel to the *c* axis. Negative curvature in such experimental geometry may be caused by the effect of twins that act as strong pinning centers in the $YBa_2Cu_3O_{6.95}$ superconductor. Indeed, the activation energy of vortices trapped by twin boundaries obeys (Ref. 2), $U \sim J^{-1/4}$ or $U \sim J^{-1}$ (for vortex motion along or off twin planes, respectively), and both current dependencies of the activation energy imply the negative curvature of $E(J)$ curves plotted in double logarithmic scale.

III. CONCLUSIONS

We measured current-voltage characteristics of $YBa_2Cu_3O_{6.95}$ single crystals for transport current densities up to nearly 10^4 A/cm^2 in a geometry where we may neglect pinning by twin planes. From measurements at different temperatures and fields we obtained the range of T-B values where a ln$E$ vs $J^{1/2}$ plot of CVC's yields straight lines as expected for plastic creep of the flux-line lattice. Determination of the depinning critical current density allowed us to derive the T-B-J dependence of the plastic pinning potential $U_{pl}(B,T,J)$ and to compare it with the results of Abulafia *et al.*[1] obtained by the method of local magnetic relaxation.

ACKNOWLEDGMENTS

We wish to acknowledge the financial support through NATO Collaborative Research Grant No. HTECH.CRG 961402.

---

*Electronic address: pissas@cyclades.nrcps.ariadne-t.gr

[1] Y. Abulafia, A. Shaulov, Y. Wolfus, R. Prozorov, L. Burlachkov, Y. Yeshurum, D. Majer, E. Zeldov, H. Wühl, V. B. Geshenbein, and V. M. Vinokur, Phys. Rev. Lett. **77**, 1596 (1996).

[2] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).

[3] V. Geshkenbein, A. Larkin, M. Feigel'man, and V. Vinokur, Physica C **162-164**, 239 (1989).

[4] J. Bardeen and M. J. Stephen, Phys. Rev. **140**, A1179 (1965).

[5] R. H. Koch, V. Foglietti, W. J. Gallagher, G. Koren, A. Gupta, and M. P. A. Fisher, Phys. Rev. Lett. **63**, 1511 (1989); C. Dekker, W. Eidelloth, and R. H. Koch, *ibid.* **68**, 3347 (1992).

[6] P. L. Gammel, L. F. Schneemeyer, and D. J. Bishop, Phys. Rev. Lett. **66**, 953 (1991); T. K. Wortington, M. P. A. Fisher, D. A. Huse, J. Toner, A. D. Marwick, T. Zabel, C. A. Feild, and F. Holtzberg, Phys. Rev. B **46**, 11 854 (1992).